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TRENDS OF SEASONAL HAZINESS AND SULFUR EMISSIONS OVER THE EASTERN U.S.

by

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Cooperative Agreement No. 813357

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Reduction in visual range in the eastern U.S. is caused largely by sulfate particles. Therefore, it is expected that the spatial distribution and temporal trend of man-made haziness will, to some extent, correspond to the spatial-temporal pattern of sulfur emissions. The purpose of this study is to examine the sulfur emission-haze relationship using regionally and seasonally disaggregated SO_2 emissions and visual range data. Across much of the Northeast the wintertime haziness has been either declining or slightly increasing over the past three decades. On the other hand, the summertime haziness has been generally increasing in all areas of the eastern U.S. The monthly sulfur emissions for individual states were reconstructed using yearly emission trends and seasonal emission rates. Before 1970 winter emissions were greater but since the 1970's the summer emissions have become comparable in magnitude. Comparisons of sulfur emissions and haziness are shown in Figure 1. In the northeast there is a general correspondence in the trends: a decline in the winter season and an increase during the summer. In the southeastern states there is also a close correspondence between emissions and haze trends, particularly in the summer season. These relationships may be used as a first indication of how visibility might change with changes in SO_2 emissions.

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ABSTRACT

The seasonal sulfur emission trends for individual regions are compared to the measured trends in atmospheric haziness. The monthly sulfur emissions for individual states going back to the 1800's were reconstructed using yearly emission trends contributed by earlier studies. The seasonal emission rates prior to 1975 were estimated from seasonal fuel consumption data. Our results indicate that before 1970 winter emissions were greater, but since the 1970's the summer emissions have become comparable in magnitude. In the southeast there was a clear crossover from a winter peak prior to 1970 to a summer peak since 1970. The comparison of sulfur emissions and haziness in the northeast shows a general correspondence in the patterns: a decline in the winter season and an increase during the summer. The haziness generally shows more random fluctuations. In the southeastern states there is also a close correspondence between emissions and haze patterns particularly in the summer season. This qualitative exploration of cause-effect relationship could be quantified in the future by the proper use of a retrospective regional visibility model that incorporates emissions and meteorological data. The remarkable correspondence between sulfur emissions and extinction coefficient, when these are disaggregated on a regional and seasonal basis, suggest that this relationship may be used as a first indication of how visibility might change with changes in emissions of sulfur dioxide.

INTRODUCTION

The reduction of visual range is caused primarily by particles in the size range 0.1-1 micrometers. From the point of view of visibility, the most significant chemical species of submicron particles are sulfates. Therefore, it is expected that the spatial distribution and temporal trend of man-made haziness will, to some extent, correspond to the spatial-temporal pattern of sulfur emissions.

A major goal of our ongoing research has been to document the relationship between the measured patterns of haziness and the driving forces of change including emissions. Previous reports dealt with the spatial and temporal patterns of eastern U.S. haziness (Husar and Patterson, 1981); haze climate of the United States (Husar and Patterson, 1986); and eastern U.S. haze trends during the 1978-82 mini-recession (Husar, et al, 1987).

The purpose of this report is to examine the sulfur emission-haze relationship using seasonal disaggregated SO_2 emission and visual range data. The motivation for this study arose from the observation of the regional and seasonal dependence of haziness. Across most of the Northeastern states, for example, the wintertime haziness has been either declining or slightly increasing over the past three decades. On the other hand, the summertime haziness has been generally increasing in all areas of the eastern U.S. The question was then phrased whether the differences in seasonal haziness trends could be attributed to seasonal shifting of the emission trends.

YEARLY AVERAGE AND SEASONAL SULFUR EMISSION TRENDS

Recently, there have been several compilations of yearly sulfur emission trends: Gschwandtner, et al, (1975); Husar (1986); and monthly trends (Knudson, 1985). The sulphur emission trends used in this study utilize all three of the above data sources along with data collected for this study. The details for the procedures are presented elsewhere (Husar, 1989).

The resulting sulfur emission trends for the contiguous U.S. and the eastern U.S. are presented in Figure 1. The trends for both regions show a wavy pattern with the last peak occurring in the early 70's. Since then there has been a remarkable decline in emissions that is comparable to the low values during the 50's and the 30's. It is also noteworthy that during the past century the fraction of the eastern U.S. emissions has remained about 70% of the national emissions, resulting in essentially no drift from east to west. It will be noted later that there was a substantial drift of emissions from north to south.

The emissions of sulphur oxides exhibit a strongly seasonal pattern over most of the country. The seasonal trend is driven largely by climatic variables such as temperature. In the winter season the low temperatures cause higher emissions due to heating in the residential and commercial sector. Similarly, in the summertime, high electricity consumption is caused by cooling requirements. Both heating and cooling demand depend strongly on geography. Thus, the resulting seasonal amplitude varies from state to state.

The pattern resulting from the variation in of monthly sulfur emissions, as compiled by Knudson, is illustrated below. The national average SOx seasonal pattern (Fig. 2a) shows a peak in January and another in July. The seasonal pattern is largely contributed by the electrical utility sector. The additional figures for other states (Figures 2b, 3a,b and 4a,b) illustrate that the northern states have a winter peak while the southern states exhibit a peak during the summer.

We have used Knudson's monthly sulfur emission data (1975-1984) to estimate the historical seasonality for the period 1860-1975. For years prior to 1975 we have adjusted the emission seasonality using historical monthly fuel consumption data. The details of the seasonal reconstruction are given elsewhere (Husar, 1989).

The results of our computations are illustrated in Figures 5-8. Figure 5 shows the trends of the national U.S. sulfur emissions for January and July. It shows that until the 1970's the January emissions were almost a factor of two greater than those

in July but the difference has been reduced in the 80's. The pattern for individual states shows that there was a general increase in the summer emissions relative to the winter emissions, particularly for the southeastern states. In Georgia, for example (Figure 6b), the January emissions in the 1920's were 30% higher than the July emissions. By the 1980's the July emissions were higher by the same factor. Similar transitions occurred in North Carolina but the seasonal amplitudes were less pronounced. In New York and Minnesota(Figures 7a and 7b), the January emissions have remained higher throughout the century but the winter-summer difference has been reduced. It is thus evident that the seasonal amplitude and the phase shift over time is regional in nature and has to be estimated for each state.

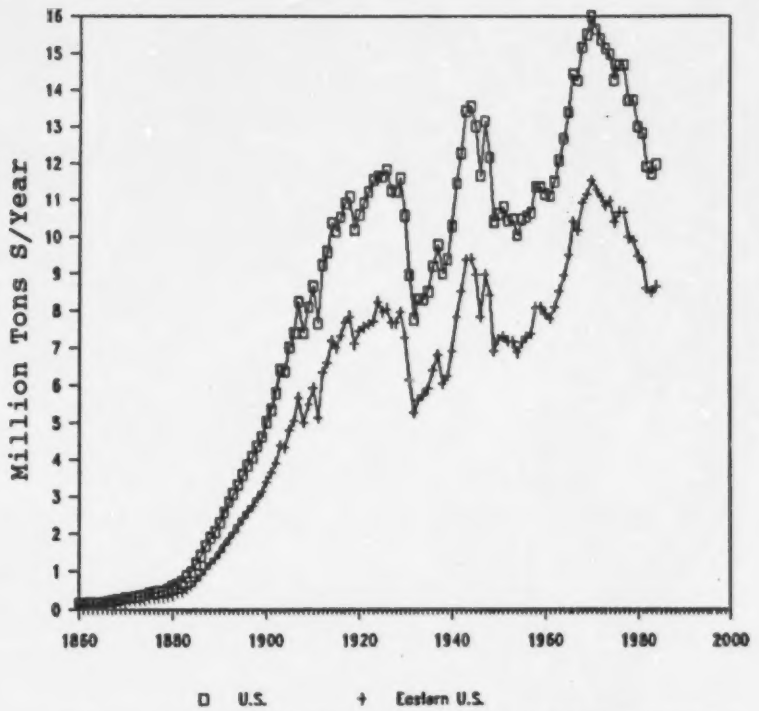
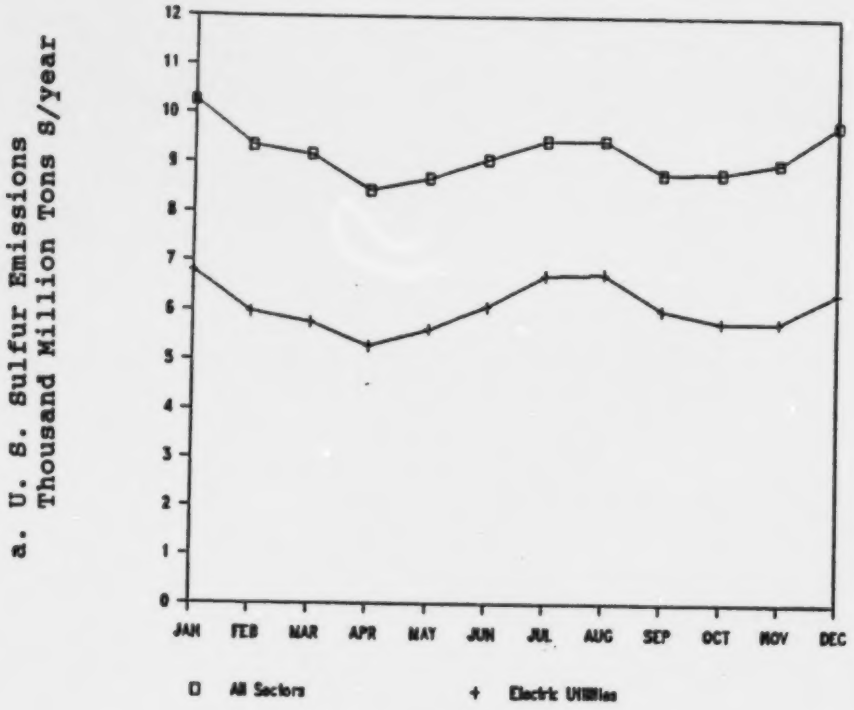


Fig. 1 Historical sulfur emission trends for the contiguous U.S. and for the eastern U.S. (east of Mississippi) (Husar, 1986).



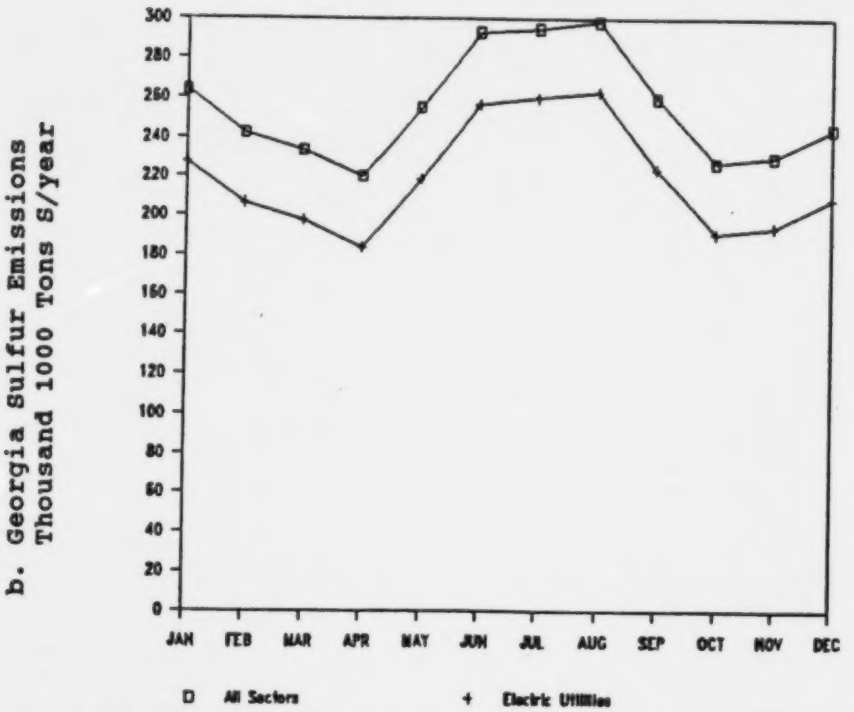


Fig. 2. Seasonal patterns of a. sulfur emissions for U. S. and Georgia, 1975-1984 average (Knudson, 1985).

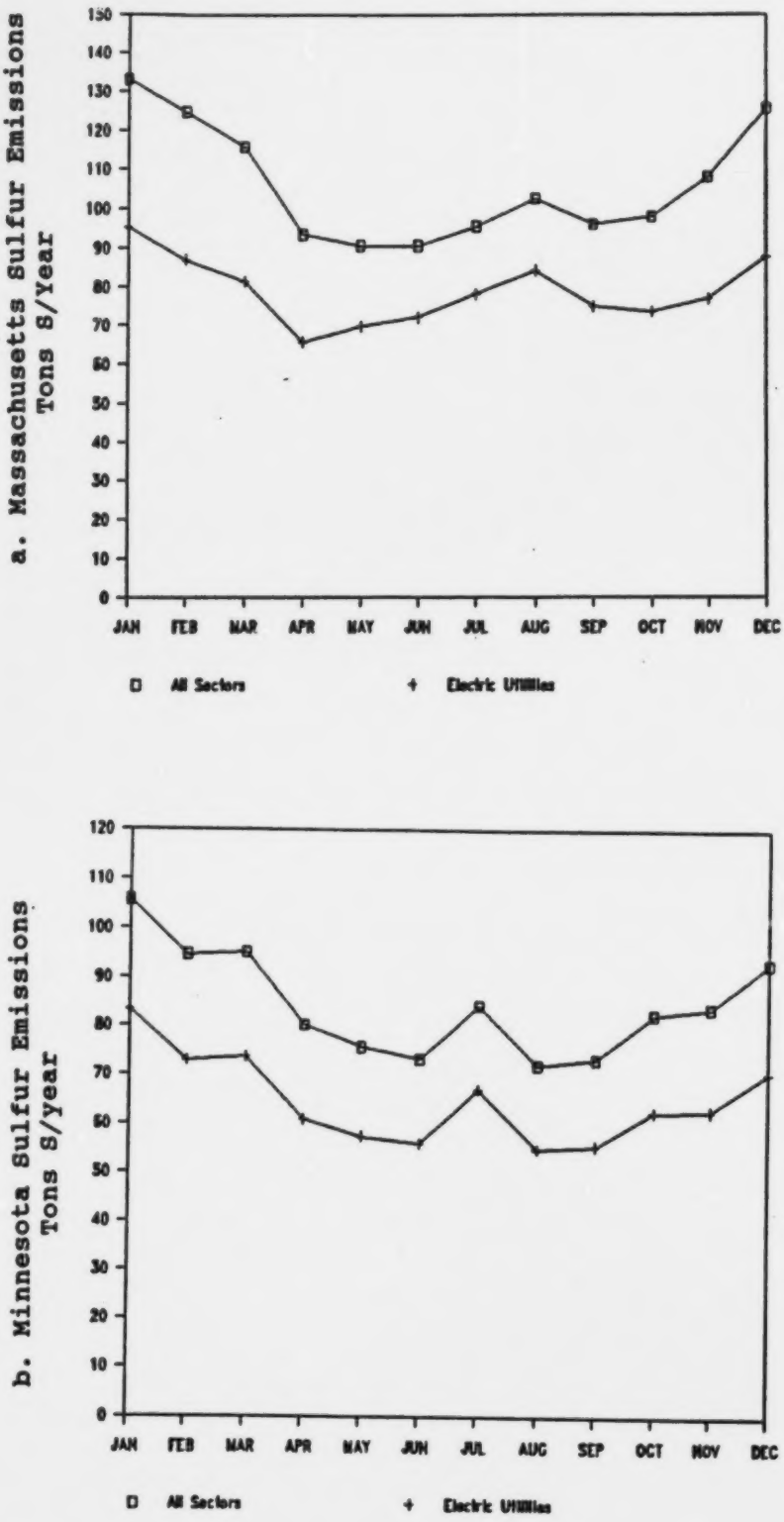
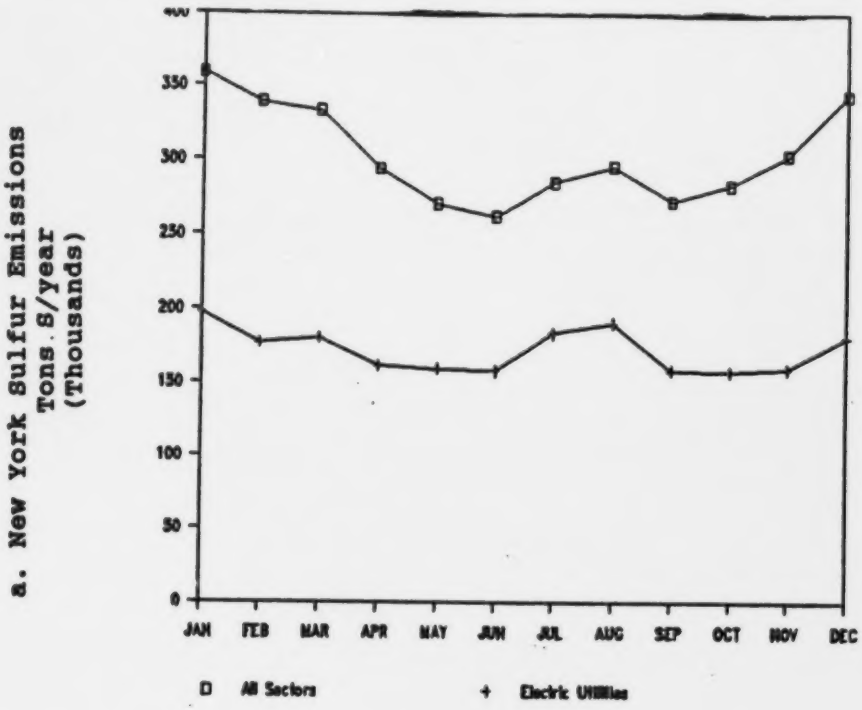


Fig. 3. Seasonal patterns of a. sulfur emissions for a Massachusetts and b. Minnesota, 1975-1984 averages (Knudson, 1985).



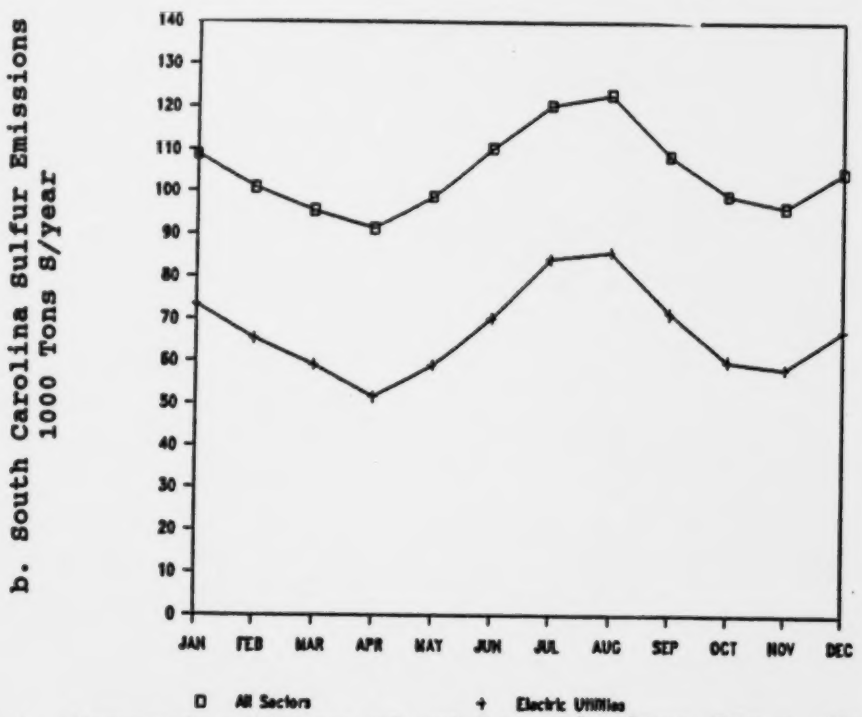


Fig.4 Seasonal patterns of sulfur emissions for a. New York b. South Carolina, 1975-1984 average (Knudson, 1985)

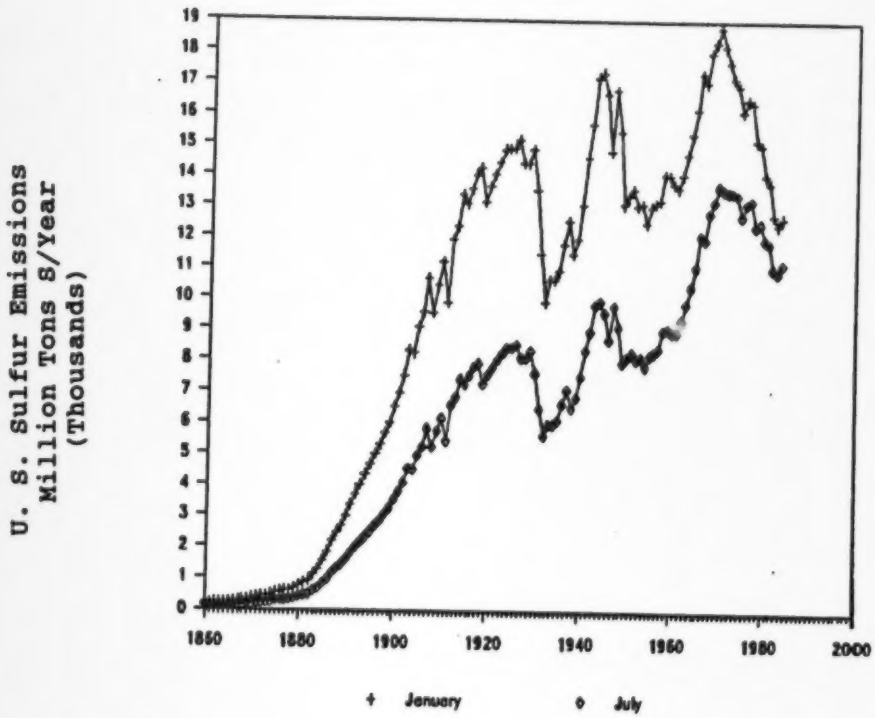
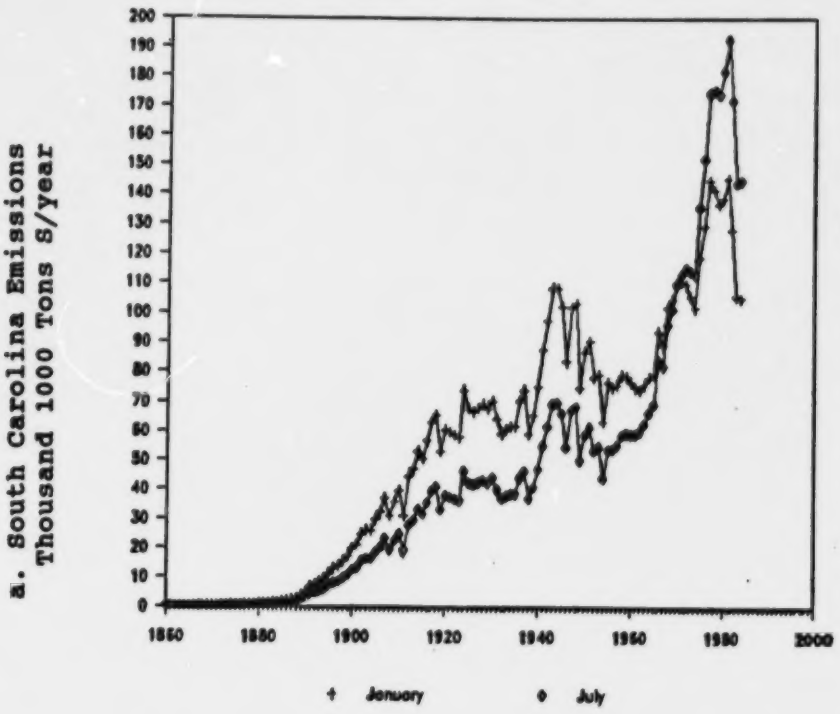


Fig. 5 Sulfur emission trends for January and July for contiguous U.S. (Husar, 1989).



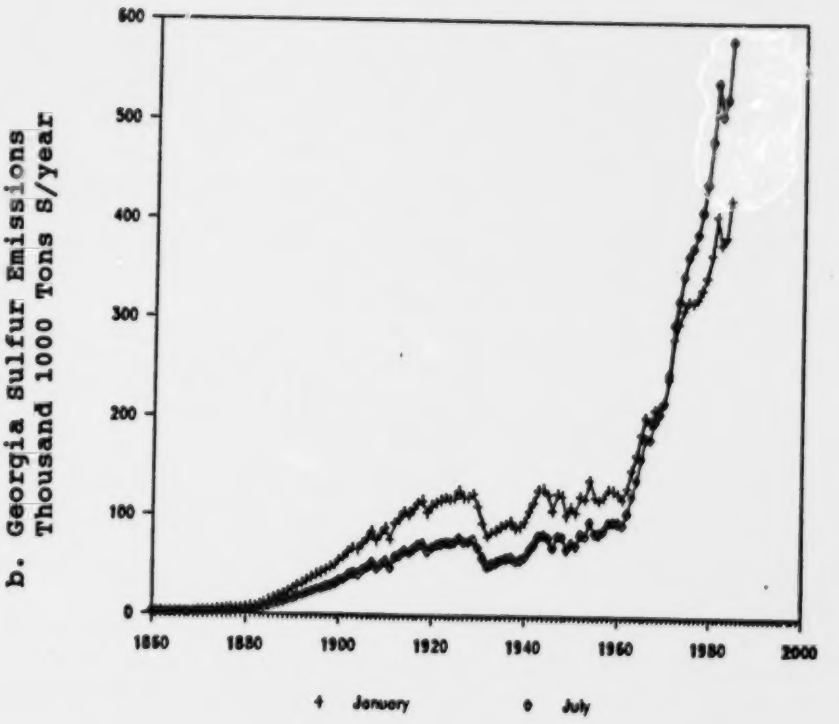


Fig. 6. Sulfur emission trend for January and July for South Carolina and Georgia.

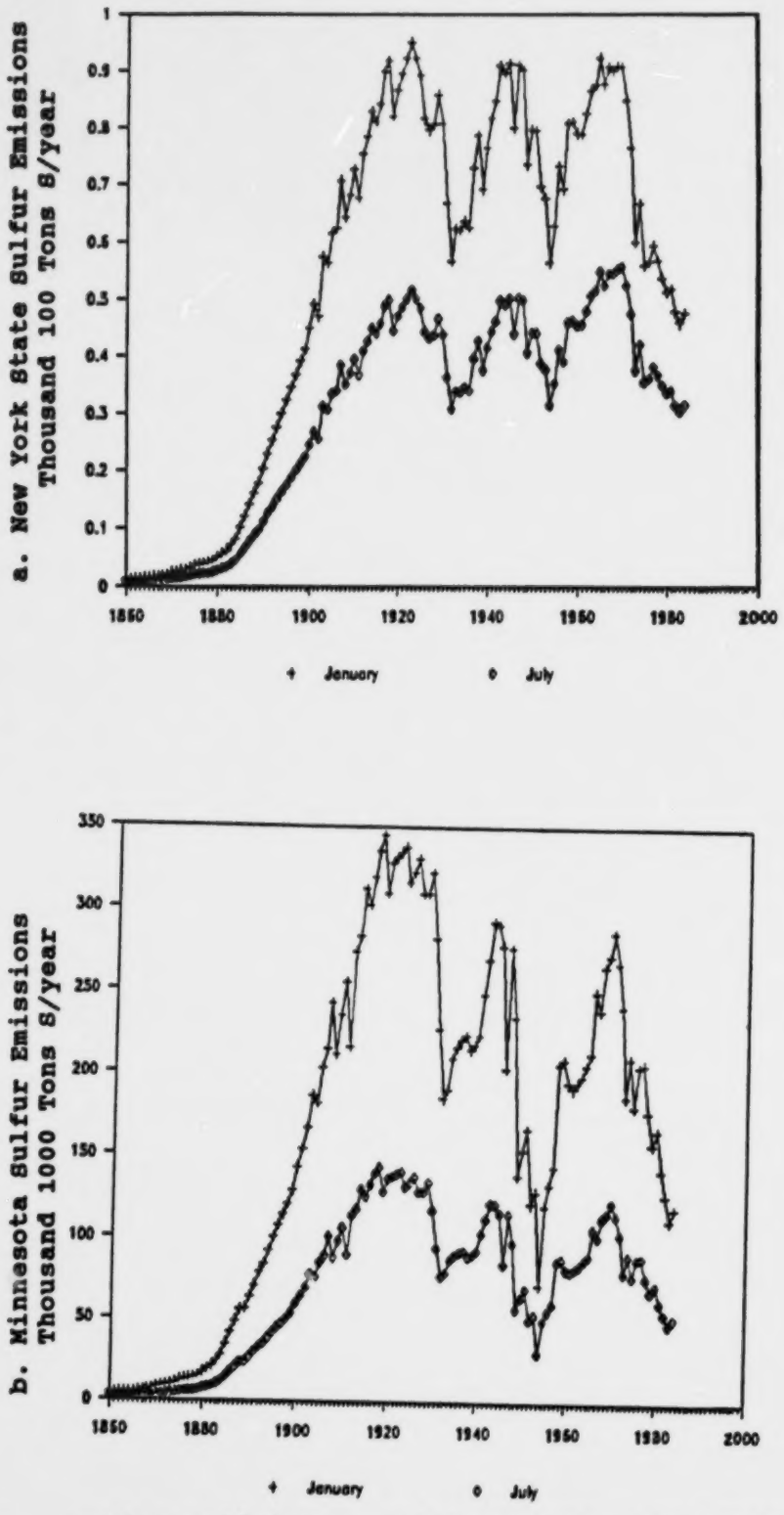


Fig. 7. Sulfur emission trends for January and July for New York and Minnesota.

For purposes of summary and comparison with the haze data, it is instructive to observe the seasonal emission trends aggregated over regions; e.g., the Northeast (Illinois, Indiana, Ohio, Pennsylvania, and New York), (Fig. 8a) and the Southeast (Tennessee, North Carolina, South Carolina, Georgia, Alabama, and Louisiana), (Fig. 8b). In the Northeast, the winter (January) emissions were about 50% higher over most of the century but became comparable in magnitude to the summer emissions by the 1970's. In the Southeast there was a clear shift from a strong winter peak to a summer peak. The crossover occurred in the late 70's.

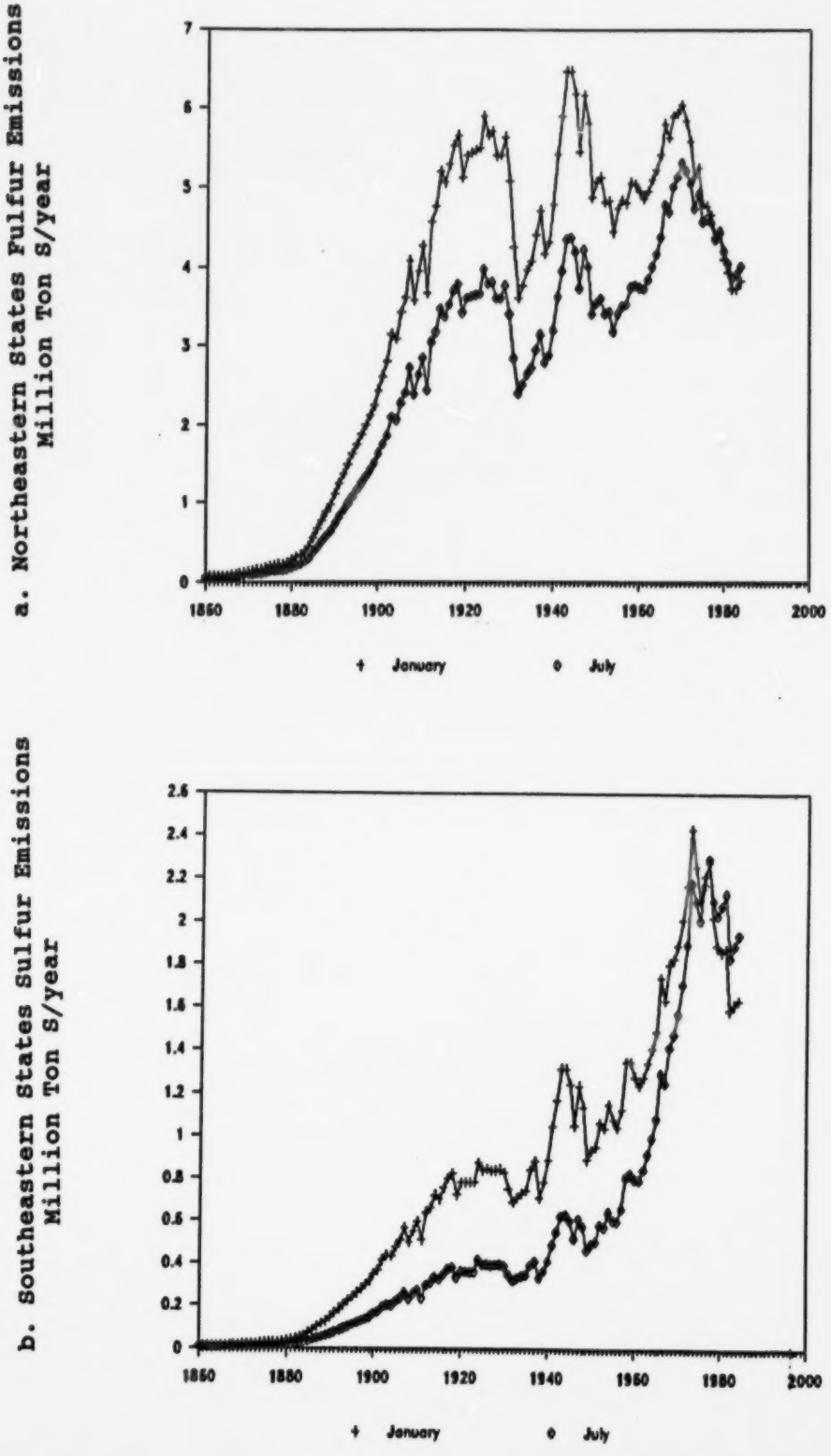


Fig.8 Sulfur emission trends for January and July for a. northeastern and b. southeastern states (Husar, 1989)

REGIONAL TRENDS OF HAZINESS

In this section visibility data are analyzed for regional haze trends over the eastern United States. This will facilitate a comparison of regional sulfur emission trends and regional haze trends as presented in the next section. We have chosen to discuss the trends in terms of haziness instead of visibility since haziness increases as pollution increases. The extent of haziness, or reduction in visual air quality, is related to the amount of light scattering and absorption by particles and gases. The extinction coefficient is a quantitative measure of haziness.

Haziness is the inverse of the visual range. The visual range is the maximum distance at which an observer can discern the outline of a black object against the horizon sky. Values of ground-level visual range are recorded every hour at several hundred National Weather Service meteorological stations within the U.S. The visibility trend data base consists of 137 stations for which computerized data is available since 1948. The quantitative measure of haziness is the extinction coefficient, b_{ext}, and is calculated from the visual range by the Koschmieder relationship, b_{ext} = 24/visual range, miles, where 24 is derived from the Koschmieder relationship, assuming the eye can just detect a 2% contrast difference between a black object and the sky. (Koschmieder, 1924).

The excellent spatial and temporal coverage of the visibility data base can be utilized only after careful site by site scrutiny for anomalous behavior. For example, one problem with visual range measurements is that there is always a farthest object or visibility marker beyond which the visual range is not resolved. This translates to a lower threshold value for the computed extinction coefficient. For this reason, the mean visual range is inappropriately biased upward. Therefore, more reliable nonparametric statistical indices are needed. In their Summary of Haze Climate of the United States, Husar and Patterson (1986), analyzed monthly extinction coefficients for each station. They concluded that use of the 75th percentile would provide a robust, reliable measure which would not be unduly influenced by the threshold value.

Therefore, for this study we have chosen to present the trends in terms of the 75th percentile. Details of the technique and trend plots for each station may be found in Husar and Patterson (1986).

The geographic pattern of haziness is presented in the sixteen maps found in Fig. 9: one map for each of the four seasons and four time periods. These maps show the 75th percentile of the noontime extinction coefficient in the absence of fog and precipitation corrected for the effect of relative humidity. Since sulfate particles grow in size as relative humidity increases and therefore scatter light more efficiently at higher humidities, we have chosen to adjust the extinction coefficient to what would be expected at 60% RH. The correction serves primarily to reduce the extinction coefficient at relative humidities above 80% and make the corrected extinction coefficient a better measure of pollution. The winter season haziness is most pronounced over the Great Lakes and the Gulf states. Pennsylvania, New Jersey and New York and parts of New England show declines of haze between the 1950's and 1980's. The most significant winter time increase is noted for the Gulf states, Louisiana, Alabama, Mississippi and Georgia. The second and third quarter haziness show an increase over all states east of the Rocky Mountains, particularly in the Gulf States. With the notable exception is the declining haziness in the Ohio region, the fourth quarter closely resembles the maps of the first quarter.

For quantitative examination of the regional trends it is advantageous to plot the trends for several stations aggregated over a given region. Figures 10a and 10b show the January trends of haziness in the Southeast (Tennessee, North Carolina, South Carolina, Georgia, Alabama, and Louisiana), and over the Northeast (Illinois, Indiana, Ohio, Pennsylvania, and New York). Fig. 10,a,b, and 11,a,b, show the January and July trends for these two regions.

We find the above regional changes in haziness enlightening in that specific regions such as the Northeast and the Gulf region show coherent trends. However, the tendencies of the trends are significantly different in the north and south. In the Northeast the January haziness shows about a 40% decline over the 35 years record, while in the Southeast there was about a 10% increase in the January haze.

The July haziness in the industrialized northeastern states shows a general increase of about 40% in the 1960's compared to the 1950's with evidence of a decline after 1978. In the southeastern states, on the other hand, there was more than a factor of two increase in summer haziness occurring mainly in the 1950's and 1960's.

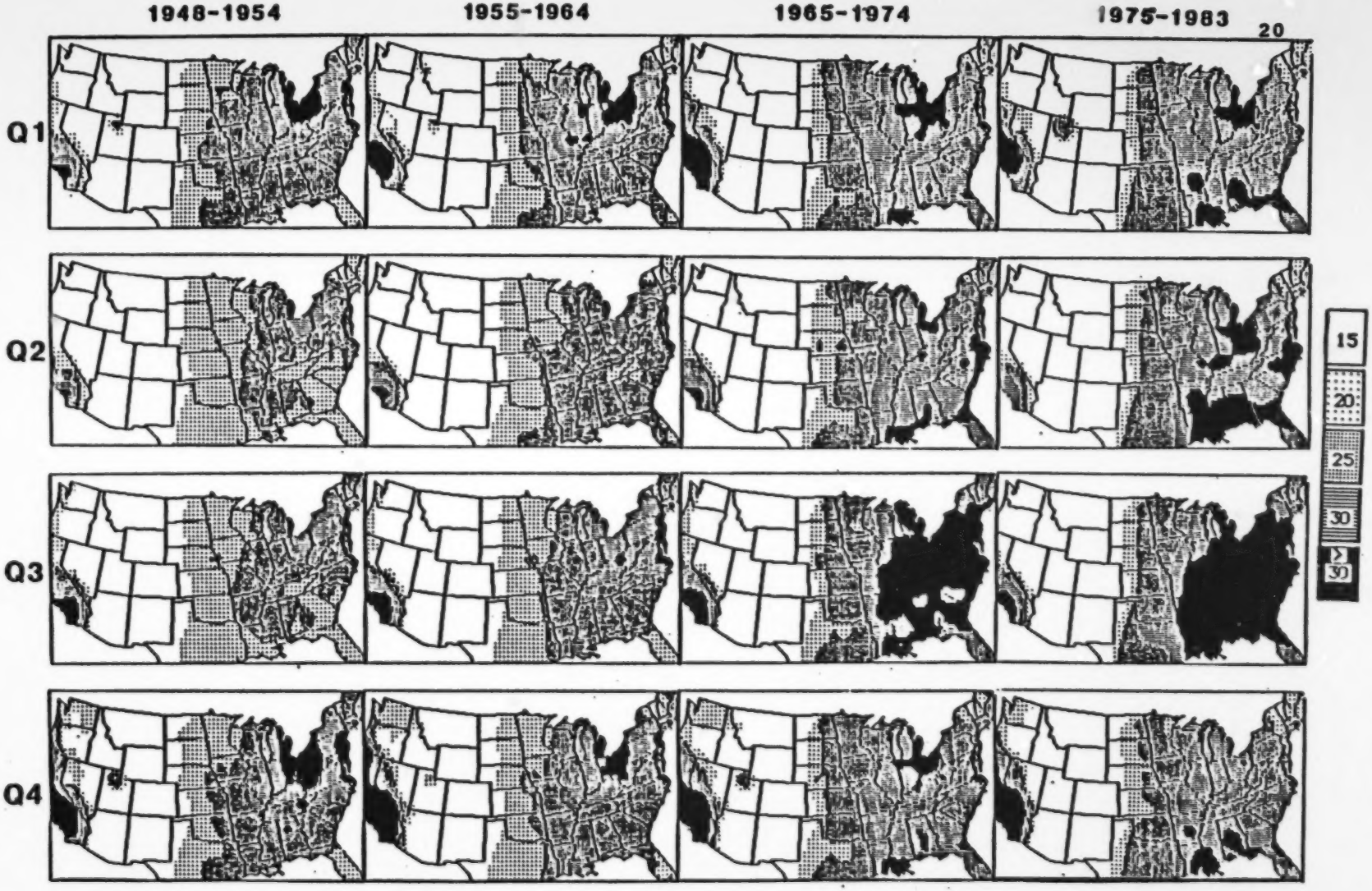
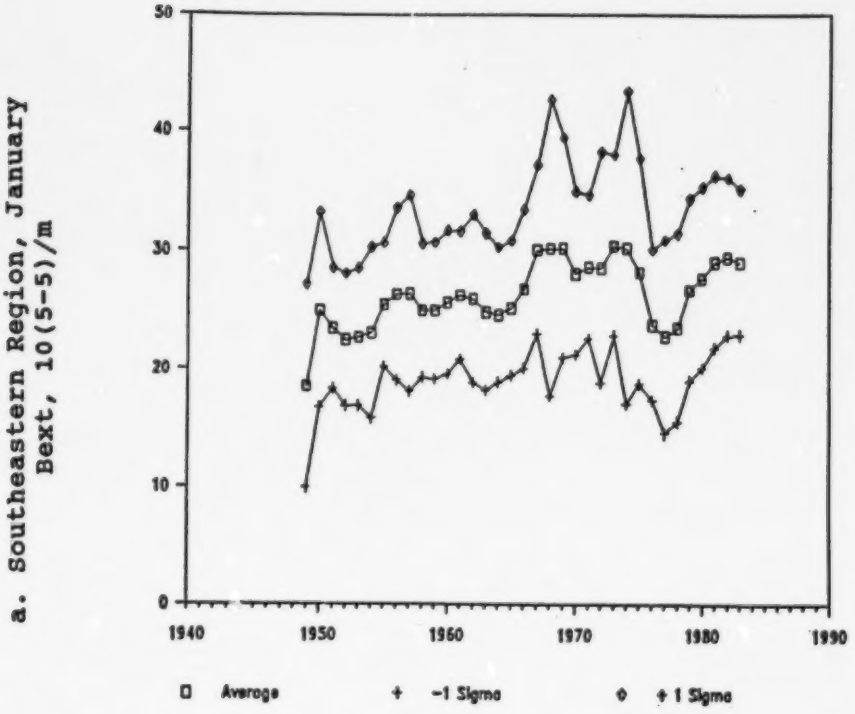


Fig. 9 Trend maps for U.S. haziness for winter (01), spring (02), summer (03), and fall (04). The units are the 75th percentile of the extinction coefficient, 10^{-5} m^{-1}.



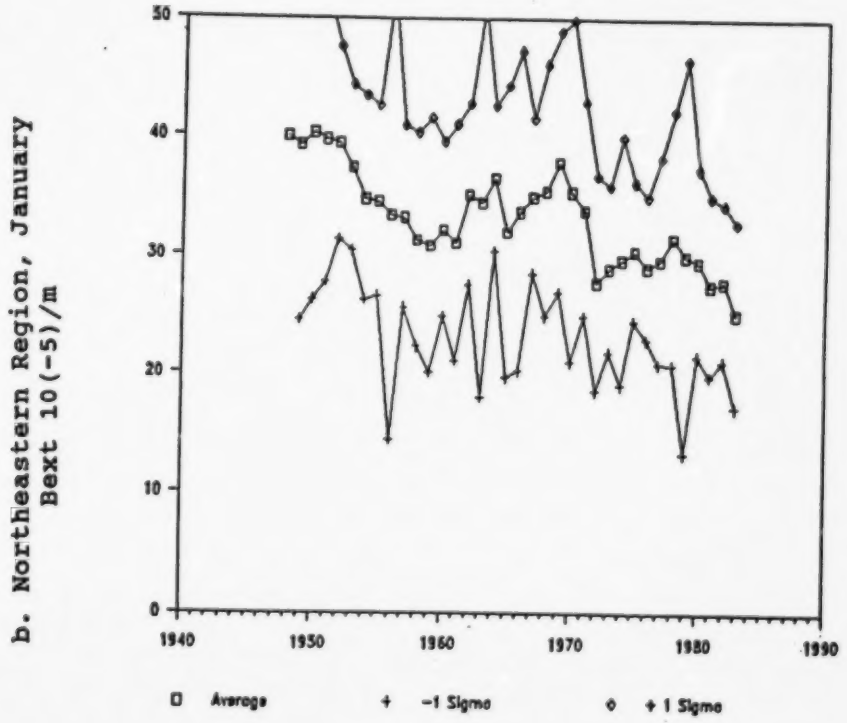


Fig. 10. Trend of January extinction coefficient for the a. southeastern and b. northeastern regions.

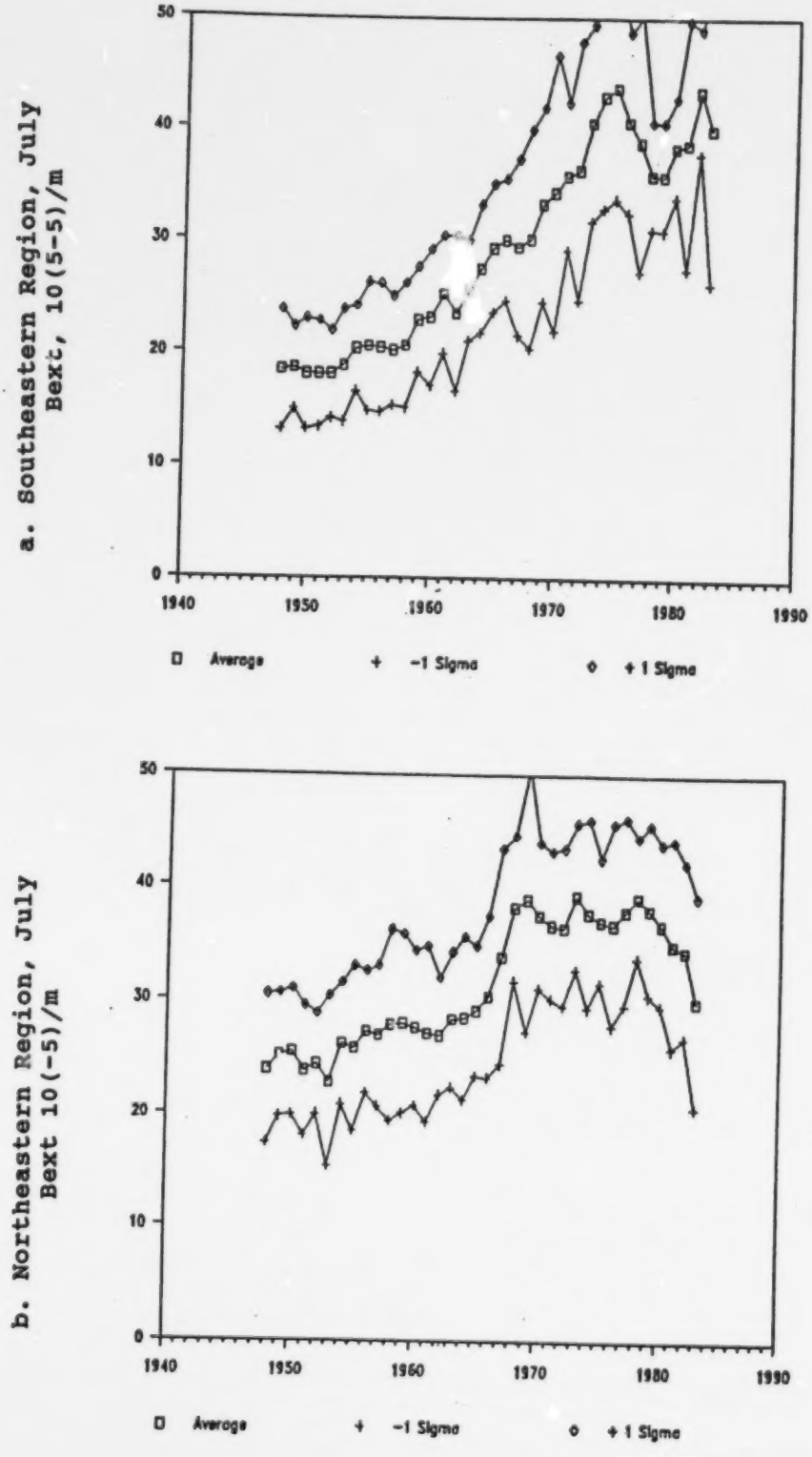


Fig. 11. Trend of July extinction coefficient for a. southeastern and b. northeastern regions.

COMPARISON OF HAZE AND EMISSION TRENDS

In this section a qualitative comparison is made between the seasonal sulfur emission trend data and the visibility trends. The comparison is again broken down by region and season.

The trends of haze and sulfur emissions for the northeast in January are depicted in Figure 12a. The emissions show a peak in 1943-44 and in 1970 followed by a significant decline thereafter. Overall, there was a general decline during the period of record. The wintertime haziness also exhibits a general decline but shows more year-to-year fluctuations. The corresponding trends for July are illustrated in Figure 12b. The July emissions again show the two peaks, but the peak around 1970 is more pronounced and the decline since 1970 is not as significant as the decline of January emissions. The summertime haziness in the northeast shows the lowest values prior to 1967 with a significant increase thereafter. Since about 1970 there was no significant decline except for 1983. Overall, the emission and haze patterns show close correspondence in the 1950's and 60's but they deviate for several years after 1971.

The January haze and emission trends for the southeast are shown in Figure 13a. The emissions rose slightly until 1973 and then declined. The January haziness also shows a slight increase in the 50's to the early 70's followed by a major decrease after 1974. There is no corresponding pattern in the emission trends. The comparison of July sulfur emissions and haziness for the southeast is found in Figure 13b. It shows a remarkable correspondence of the two parameters indicating increasing values from the late 40's through the early 70's followed by a leveling off since then.

It is to be noted that in all of these comparisons the extinction coefficient is plotted with an offset of $10^{-5}/m^{-1}$. This offset may be viewed of a crude estimate for the background b_{ext} arising from natural sources.

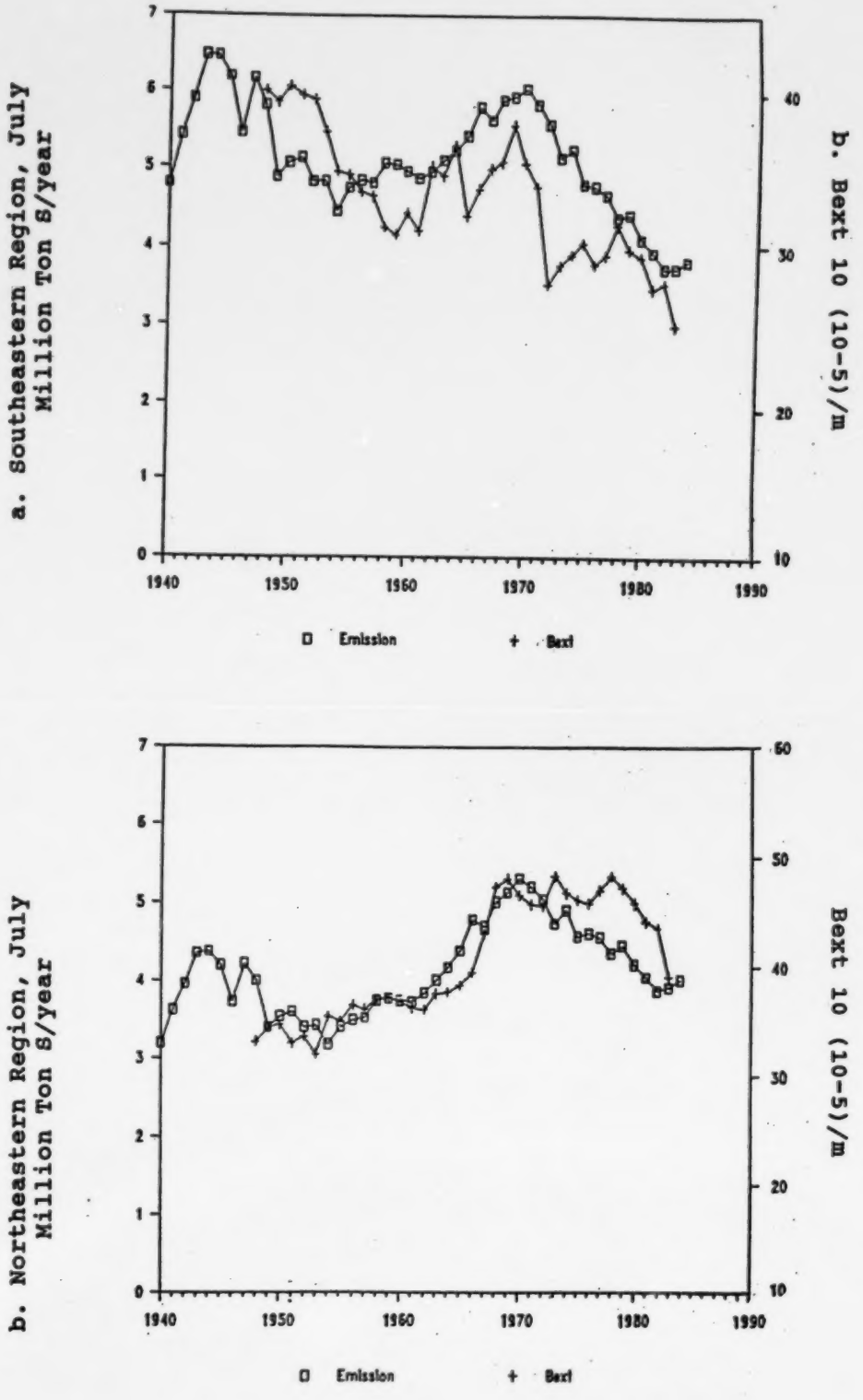
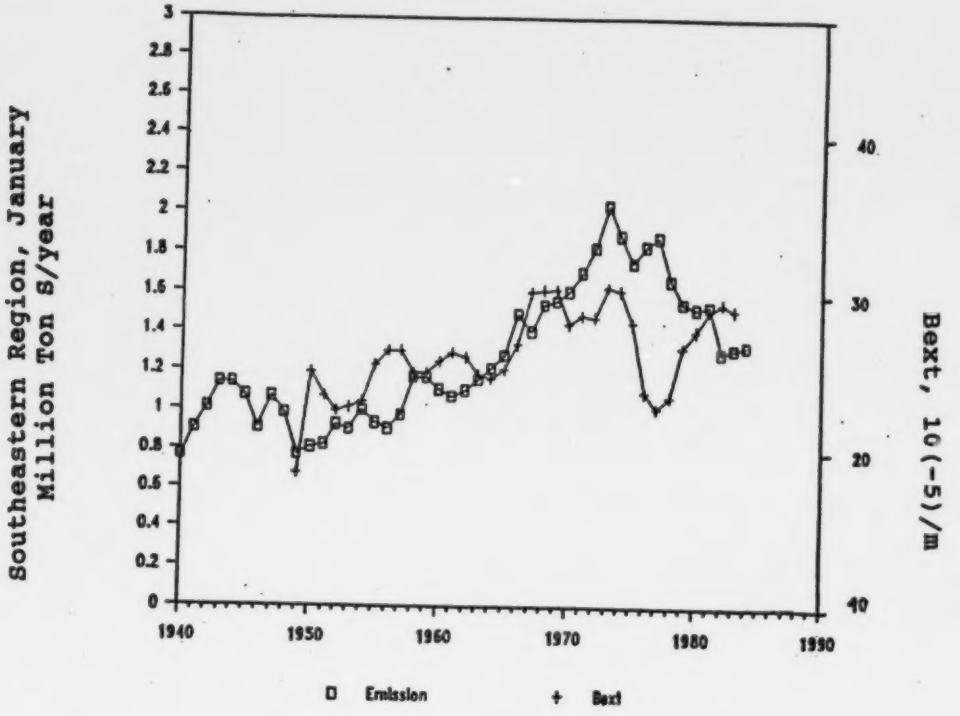


Fig.12 Comparison of trends of sulfur emissions and extinction coefficient for the northeastern region: a. January, b. July



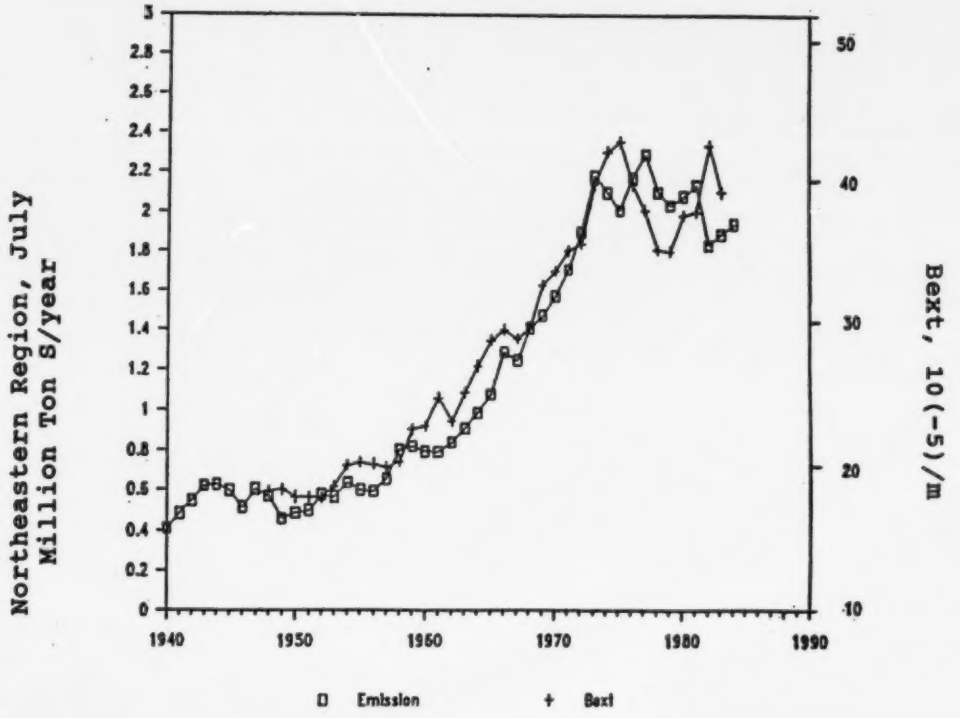


Fig. 13. Comparison of trends of sulfur emissions and extinction coefficient for the southeastern region: a. January b. July

SUMMARY AND CONCLUSIONS

In this study the seasonal sulfur emission trends for individual regions are compared to the measured trends in atmospheric haziness. The monthly sulfur emissions for individual states going back to the 1800's were reconstructed using yearly emission data contributed by Gschwandtner (1975), Knudson (1986), and Husar (1986) with the monthly estimates by Knudson. The seasonality of emissions prior to 1975 was estimated from seasonal fuel consumption data. Our results indicate that before 1970 winter emissions were greater, but since the 1970's the summer emissions have become comparable in magnitude. In the southeast there was a clear crossover from a winter peak prior to 1970 to a summer peak since 1970.

The comparison of sulfur emission and haziness in the Northeast shows a rough correspondence in the tendencies: a decline in the winter season and an increase during the summer. The haziness generally shows more random fluctuations. In the southeastern states there is also a close correspondence between emission and haze patterns particularly in the summer season.

In conclusion, the results of this study show that trends in the seasonal sulfur emission patterns correspond to the observed seasonal trends of atmospheric visibility; however , such qualitative comparisons do not provide conclusive evidence of cause-effect relationship. Also, the pattern of haze and sulfur emissions for the Northeast and Southeast tend to deviate at times. The causes of such deviations may include variabilities due to meteorology as well potential errors in both emission and haze data. Finally a one-to-one relationship cannot be expected since the haziness in one region may be influenced by emissions in the neighboring regions. If the emission trends are different for each region, atmospheric processes would tend to smear out the regional haze trend. A more detailed emission-haze trend analysis could be conducted using a regional haze model that incorporates both the changes in the emissions as well as the meteorological data for individual years. Both emission and wind data sets are available for such retrospective model studies.

The relative significance of chemical species and source types that influence visibility, other than sulfur, were not examined in this current analysis. Hence, it can not be excluded that other compounds may not have similar emissions and trend patterns as sulfur. For future studies it would be desirable to examine the emission trends of other potential visibility-reducing species; e.g., organics, flyash, soot, etc., in order to estimate their contributions. The relative importance of such species could be estimated through historical emissions, chemical data on atmospheric aerosols, lake sediment cores, and other "diaries" of nature where historical data are kept.

From other information (NAPAP, 1987) it is known that in the eastern U.S., at least in the last decade, sulfate, formed in the atmosphere from sulfur dioxide, and the ammonium and condensed water associated with the sulfate, dominates the light-scattering particulate matter in the ambient air. The remarkable correspondence between sulfur emissions and extinction coefficient, when these are disaggregated on a regional and seasonal basis, suggest that this relationship may be used as a first indication of how visibility might change with changes in emissions of sulfur dioxide.

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